GPS-LIKE TRACKING (GLT) OF GEOSYNCHRONOUS SATELLITES: 01<111'1' DETERMINATION RESULTS FOR TDRS AND INMARSAT

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We describe results from two recent experiments in which Global Positioning System (GPS) technology was applied to precisely determine the orbits of geosynchronous satellites. The experiments demonstrate different aspects of a technique which wc call C]PS-like tracking, (GLT). in the ideal realization of GLT, a ground-based network tracks a pseudo-GPS signal from a user satellite together with standard positioning, timing and mitigation signals from the GPS constellation. The cornerstone of the ground network is an enhanced GPS receiver capable of making precise, simultaneous measurements of the signals originating from both the GPS and user satellites. The simultaneous measurements enable exploitation of powerful differential GPS techniques to precisely determine station coordinates, calibrate media delays and eliminate timing errors among widely dispersed tracking stations.

In the first experiment, wc apply a promising short- baseline variation of GLT to determine precise orbits for NASA's geosynchronous Tracking and Data Relay Satellites (TDRS). The technique uses only the existing narrow-beam TDRS space-to-ground link (SGL): the phase of the SGL carrier is tracked directly in modified GPS receivers and no pseudo-GPS signal from TDRS is required. In the second demonstration, measurements of a pseudo-GPS range signal from tbc Inmarsat-2 (AOR West) geosynchronous satellite were taken at two sites in the continental 11. S. and subsequently used in computing a precise ephemeris. Our results suggest that root-mean-square (l< MS) precisions of tbc TDRS and Inmarsat orbits determined for these demonstrations are at the level of 25 and 10 m respectively. Wc discuss the prospects that 1-m geosynchronous orbit accuracies can be achieved by using a system that features complementary aspects of these demonstrations.

INTRODUCTION

From the early development stages of tbc Global Positioning System (GPS), designers recognized its potential as a powerful tool for tracking Earth-orbiting spacecraft. With the completion of the GPS constellation in 1994, and the considerable success of recent spaceborne

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GPS experiments such as Topex/Poseidon[1], the remarkable potential of the system continues to emerge. What distinguishes GPS from other tracking and orbit determination systems is its unsurpassed observability. Satellites in low-Earth orbit, Well below the Shell of the GPS constellation, are afforded continuous 3-d tracking coverage. This robust observability enables a satellite equipped with a GPS receiver to compute its state (position and velocity) without regard to the physics underlying the spacecraft motion. Of course, the traditional dynamic force modeling approach remains invaluable for many applications. A major advantage of GPS is in fact that it permits a wide diversity of orbit determination strategies- --from purely geometric to fully dynamic--depending on the application of interest.

Intuition suggests that the advantages of GPS for orbit determination will be lost at sufficiently high altitudes. There is some basis for this conclusion with the conventional GPS approach, wherein the spacecraft is equipped with a GPS flight receiver. The beams of signals from the GPS spacecraft extend about 3000 km above the Earth's limb. Users at high altitudes, e.g. geosynchronous, must therefore peer over the limb of the Earth to track the signals being emitted from GPS spacecraft on the other side of the planet. At geosynchronous altitude, on average, the signals from only one GPS satellite are visible using this "down-looking" GPS approach.[2] Uncertainties associated with the long signal path and limb-grazing geometries further underscore the inherent difficulties of this configuration.

An alternative to carrying a GPS flight receiver employs instead a GPS-like beacon on the user spacecraft. The beacon signal is tracked along with signals from the GPS spacecraft in an enhanced GPS ground receiver. This technique, herein called GPS-like tracking (GLT), exploits differential GPS to precisely determine station coordinates, and media delays and to provide clock synchronization at the ground stations[2–4]. In contrast to conventional GPS-based orbit determination, the number and distribution of *receiving* ground stations, rather than *transmitting* GPS spacecraft, determine the geometry governing the solution. * The GLT method is particularly attractive for spacecraft in high altitude orbits: while the practical observability of GPS signals degrades rapidly as a function of altitude above the GPS constellation, the number of ground stations that can be kept in permanent view of a beacon signal increases. For a spacecraft in geosynchronous orbit, a ground network can be designed that is in permanent view of the beacon signal, providing uninterrupted tracking. Even with the continuous tracking, the GLT geometry is not favorable enough in most circumstances to support a geometric-style precise orbit determination. Fortunately, owing to the attenuation of the rich geopotential signal and absence of atmospheric drag, most of forces acting on spacecraft in geosynchronous orbits are readily modeled. (A notable exception is the surface force from solar radiation pressure.)

What level of orbit accuracy can be achieved for geosynchronous orbiters using the GLT approach? We will attempt to address this in this paper, but as a starting point, we note that the GLT method is the essence of the system used to compute ephemerides for the GPS spacecraft with root-mean-square (RMS) errors of 10--30 Cm. [5] If a GPS spacecraft were simply moved to geosynchronous orbit, it is not unreasonable to expect that nearly the same. level of accuracy could be achieved .† This thought exercise represents an ideal case in which the geosynchronous orbiter broadcasts the exact same signal as the GPS spacecraft. in practice, it is unreasonable to assume

* Wu[3] called this approach *inverted* GPS because the user satellite is now a transmitter like a GPS satellite, instead of a receiver like a ground tracking site.

† There would be some degradation owing to the weak dynamic signature of a geosynchronous orbiter, as well as the amplification of errors from the Earth orientation and polar motion parameters.

that geosynchronous orbiters can be equi pped with act ua 1 GPS t ransmitters.Our interest here lies in exploring how the G] .T method can be adapted to function with a variet y of different satellite transmissions, and to satisfy varied requirements for existing geosynchronous orbiters. In this context, we present rc.suits from two recent experiments in which the GLT method was adapted to track spacecraft from the Tracking and Data Relay Satellite (TDRS) and 1 Nternat ional MARitime SATellites (I NMARSAT) geosynchronous constellations.

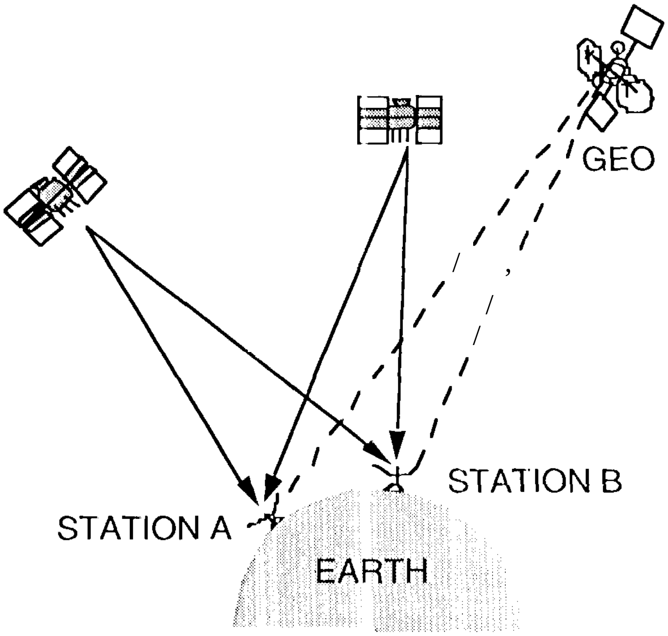

Figure 1. Differential (;I'S-like tracking (GLT) applied to geosynchronous orbiter. Simultaneous observations of GPS satellites and ground stations enable removal of transmitter and receiver clock errors. After tracking for 12-24 hours, the GPS orbits can be determined to a 10-30 cm (RMS). In GLT, data from the high-Earth orbiter is also included **and its orbit similarly estimated. This relationship is discussed further by *Lichten et 01.*[4]**

TDRS/GPS TRACKING DEMONSTRATION

An attract ive candidate for appl ying the GLT technique is NA SA'S Tracking and 1)ata Relay Satellite ('1'1)RS) S yst cm. The TDRS space segment currentl y consi sts of 5 geosynchronous orbiters and is used by NASA to support posit ioning and data relay activities for a wide variety of 1 Earth orbit ing spacecraft. Accurate real-time position knowl edge of" the TDRSS spacecraft is requi red to support certai n users: though the most st ringent current requi rement is 200" m (1 s) for the Space Transportat ion System (S'1'S), the planned Earth Observing System (EO S) platform calls for 25 m (1 s) accuracy of the '1'1)RS ephemerides.[6]

Under the direction of NASA, JPL has investigated a number of potential new strategies for determining the TDRS orbit s[3,7]. Judged the. most promising among them was a hybrid approach which combined elements of GLT with a specialized form of interferometric tracking over very short baselines (Connected Element Interferomet ry or CEI; *see Edwards et al.* 9). The short baseline scenario is necessitated by the nature of the existing TDRS space-to-ground link (SGL). The TDRS SGLs illuminate only a limited area of the southwestern U.S. surrounding the TDRS Earth station in White Sands, New Mexico (Figure 2). This precludes the use of globally dispersed stations for tracking the SGL. However, if a (31.'1' network fitting within the SGL footprints could be designed to deliver the desired accuracy, significant benefits could be gained: 1) The SGL is always on when the TDRS is servicing users, Thus the signal can be passively monitored and no TDRS services need be scheduled for orbit determination. 2) The SGL is broadcast at Ku-band (1 3.731 GHz). At this frequency, the delay caused by the presence of charged particles along the signal path (i. e., ionosphere delay) rarely exceeds a few cm in equivalent range. 3) A small ground network in the vicinity of the White Sands complex (WSC) has many operational advantages: all the sites can be readily accessed for main ntenance, and communications links to the Earth stat ion can be made reliable and short

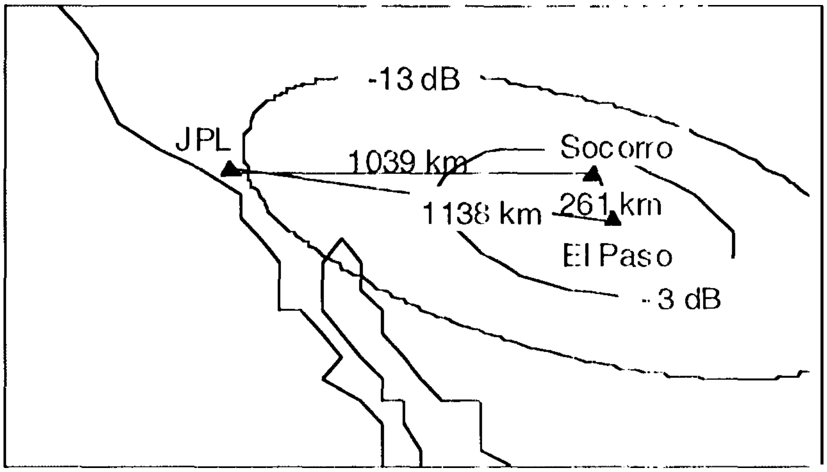

Figure 2. Configuration of TDRS/GPS tracking netw ork. The footprint of the TDRS-3 space-to-ground link (SGL) during the Jan. 1994 experiment is shown.

Following the direction of NASA, JPL designed an experiment to demonstrate the feasibility of this technique. The foundat ion of the experi ment is simult aneous tracking of GPS and TDRS signals over short baselines to determine the TDRS orbit.[4] Coincident observation of GPS and TDRS signals in the same ground receiver enables calibrations of clock errors[9-10] and tropospheric delays[11], supplanting the fiber optic links and expensive calibration devices that are needed in a connected element network. An added benefit is the ability of GPS to provide very precisely (sub cm) the positions of the tracking stations relative to one another, and tile network orientation in the terrestrial reference frame.[12]

We note that the GLT method described herein uses a measurement t ype known in the GPS community as "differential carrier phase". It is instructive to think of the phase measurement as a range observat ion that is biased by an amount corresponding to an unknown integer number of cycles along the transmission path. Each modified GPS receiver tracks the phase of the TDRS SGL with great precision (enabled by GPS). Contained in the station-differenced phase data is very precise information on the velocity of the TDRS spacecraft in the plane of the sky. Using the information in a standard dynamical orbit determination strategy determines very precisely five of the six osculating (classical) elements that describe the geosynchronous TDRS orbit. In order to determine the last component- the longitude of the satellite orbit or its down track position in inert iai space- some knowledge of the range to the spacecraft is needed. To provide this information, we used data from routine. ranging done at WSC. Additional information on the heritage of the technique, and detailed results are given in Refs. [7,13-14].

Experiment Configuration

The TDRS/GPS tracking demonstration took place from January 16-22, 1994. GPS and TDRS satellite.s were tracked simultaneously from three sites: El Paso, TX, Socorro, NM, and Pasadena, CA (Figure 2). This configuration permitted us to test the performance of side-lobe tracking, as J]'], is in a fortuitous location that placed it in the first side lobe of the SGLs from both TDRS-5 (175° W) and TDRS-3 (62° W), The other two stations, operated from motel rooms in El Paso and Socorro, were within the main beam of the SGL of both TDRS-3 and 5.

The cornerstone of each tracking, station was an enhanced TurboRogue GPS receiver. The TurboRogue, developed at J]'].15 and currently globally distributed in a 50+ receiver network used for precise GPS orbit determination and a variety of geodetic and tectonic studies[5], was augmented for this experiment with a small, Ku-band horn antenna (opening, dimensions 17 X 14 cm) and a Ku- to L-band downconverter (Figure 3). In addition, the TurboRogue software was modified to measure and record the phase of the TDRS SG1, with the same sub-mm precision and receiver time-stamp as GPS carrier phase measurements. This system architecture produces data products that significantly simplify subsequent orbit determination processing.

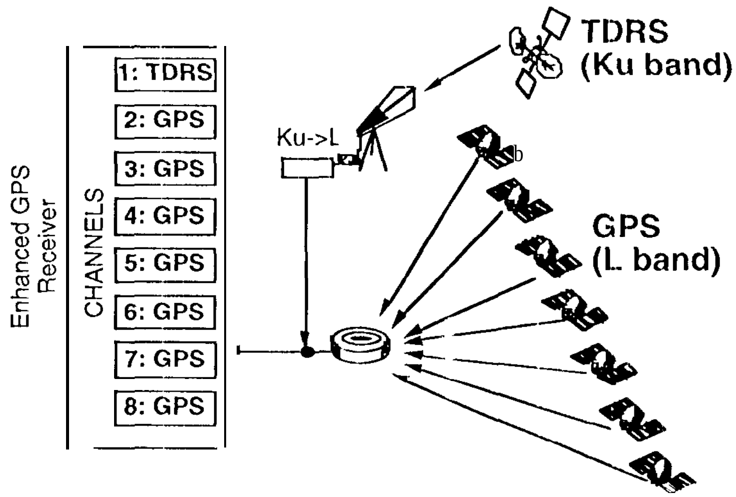

Figure 3. Schematic for the GPS ground receiver enhanced to simultaneously track TDRS along with GPS satellites. For the TDRS SGL, which is at 13.731 GHz, a small separate antenna with down converter was added.

Data collection commenced on January 16 with tracking of TDRS-3. Also known as TDRS-Central, this spacecraft was seen at an elevation of approximately 30° when viewed from White Sands. TDRS-3 was tracked for nearly 5 days before the stations were reconfigured to track TDRS-5 (January 21). This spacecraft presently occupies the western slot and is seen at an elevation of only 10° from White, Sands. Although the TDRS-5 track spanned only 18 hours, this session was useful for understanding the effects of tracking at lower elevations. Depending on the station, 85-95°/0 tracking coverage was achieved over the course of the experiment.[13]

As explained previously, ranging information to TDRS is needed to fix the longitude of the spacecraft. To satisfy this requirement, we used range observations from routine Tracking Telemetry and Control (TT&C) activities at White Sands. These observations are based on tracking of the Ku-band SGL with 18-m antennae located at the central ground terminal. The range data are not intended for precise orbit determination, and as such, they contain large systematic biases that, without calibration, preclude achievement of high accuracy in determining the longitude of the TDRS orbits. In order to estimate the range biases, we calibrated the TT&C range data against the precise TDRS orbits generated routinely at Goddard Space Flight Center (GSFC) based on the Bilateration Ranging Transponder System (BRTS).[13]

Solution Strategy

The unified TDRS/GPS orbit solutions were computed using the GIPSY/OASIS II software.[16] Table 1 outlines the solution strategy. It is similar in many respects to the strategy presently used at JPL in the routine, highly automated processing of GPS data from the much larger (80+ station) global Intl. GPS Service for Geodynamics (IGS) networks In particular, zenith wet troposphere delays were estimated as stochastic random-walk parameters, and clock offsets were estimated as stochastic white noise processes at each measurement batch. Satellite states for both the TDRS and GPS spacecraft were estimated, with *a priori* for the latter coming from the broadcast ephemerides.

TABLE 1. ESTIMATION STRATEGY FOR GPS/TDRS ANALYSIS

Data Type	Data Weight
GPS Carrier Phase	1 cm
GPS Pseudorange	1 m
TDRS Carrier Phase	1 cm
TDRS 2-way range (1/hr)	5-Q-

Models and Constants	
TDRS Solar Rad. Pressure	Bus
TDRS Area	40 m^2
TDRS Mass	1807 kg
GPS Solar Rad. Pressure	T10/T20
Earth orientation/rotation	Intl. Earth Rot. Service (Bull. B)
GPS Station Locations	Intl. Terrestrial Ref. Frame 1991
While Sands Sin. location	World Geodetic System-1984
Luni-solar Perturbations	JPL DE-200 ephemerides
Earth Gravity Field	Joint Gravity Model (JGM)-3

Estimated Parameters	Parameterization	constraint
TDRS Initial State	3-D epoch position	100 km
	3-D epoch velocity	J m/s
TDRS Solar Radiation Pressure Coefficient	constant	100%
GPS Initial States	3-D epoch position	100 km
	3-D epoch velocity	1 m/s
Troposphere	random-walk zenith delay	40 cm; 5 cm/hr$^{1/2}$
WSC 2-way Range Bias	constant	2 m
Carrier Phase Biases	constant over a continuous pass	3x10^5 km
GPS and Receiver Clocks	white-noise	1 Sec

Station coordinates for the TDRS/GPS terminals in El Paso, Socorro and Pasadena were fixed at precise values determined *a priori* using the GPS data collected at the sites.[13] The results suggest that the station coordinates have been determined at the cm level in the International Terrestrial Reference Frame. For the 18-m WSC antennae that collect the range data, we used coordinates provided by NASA in the World Geodetic System (WGS)-84 system. We did not have a GPS receiver at WSC and therefore were unable to estimate improved coordinates. Any error in this station coordinate will manifest itself as a range bias, which we estimated via external calibration.'[4]

Orbit Determination Results

We first consider four separate orbit mcs: three for TDRS-3 and one for TDRS-5. The arc lengths vary from 18 to 21 hours and span the period from January 1906: ()() UTC to January 22 13:30 UTC. Table 2 gives the statistics-of fit for the four precise TDRS orbit solutions. That the TDRS phase data can be fit nearly as well as the GPS phase is encouraging, and suggests that the TDRS data quality is excellent. Also given in the table are the statistics of the computed (formal) posit ion errors (height, cross-t rack and along-track) fort he est i mated TDRS orbit, The larger errors in tile down-track component can be attributed the WS(' range bias. As there is little strength to determine this parameter, estimating the range bias serves only to in flate the formal errors and make them more realistic,

TABLE 2. RMS TRACKING DATA RESIDUALS AN]) MAPPED '1'1)1{S FORMAL 01{111'1' ERRORS FOR TDRS/GPS SOLUTIONS.

S/C	Arc Epoch (UTC)	Arc End (UTC)	TDRS Phase (mm)	TDRS Range (m)	GPS Phase (mm)	GPS Range (m)	RMS Formal Error H (m)	C (m)	L (m)
TDRS-3	19-JAN 06:00	20-JAN 00:45	2.6	2.8	2.8	0.3	1.5	2.1	17.1
	19-JAN 2 i:00	20-JAN 17:18	5.8	1.9	3.()	0.3	1.3	2.9	15.2
	20-JAN 21:45	21-JAN 18:25	3.2	1.0	2.9	().3	1.1	1.7	13.9
TDRS-5	21-JAN 19:48	22-JAN 13:30	2.0	NA	2.7	().3	1.9	4.2	18.0

Two of the TDRS-3 orbit solutions overlap by -4 hr (Figure 4). The RMS differences of tile two solutions during the overlap is 2, 11, and 12 m in height, cross track and down track respect ively. Though the cross-track differences arc son iewhat larger than the formal errors might suggest, these results support that the orbit precision is better than 25 m (1< MS) in total position. While the formal errors and overlaps are instructive, they reveal only internal consistency. A better measure of lilt orbit accuracy is gained from external co I nparisons. To this end, wc compared our TDRS orbit solutions against the precise B1<'1'S-derived orbits from GSFC. These orbits are thought to be accurate to 50 m or better in total position (1 -σ). The comparisons were performed in the i nert ial (J2000) reference frame.

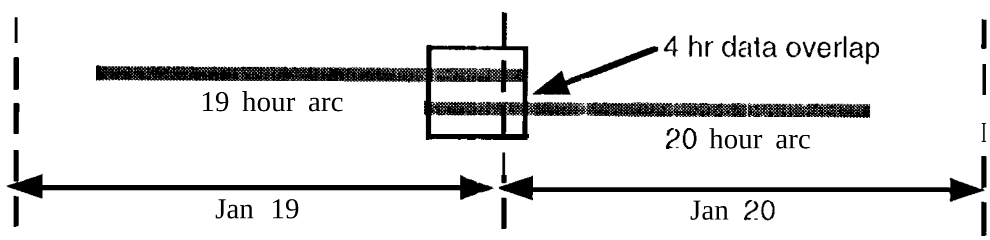

Figure 4. Schematic of orbit overlap for TDRS-3 orbit comparison]. The RMS differences height, cross track and down track arc 2, 12 and 11 m respectively.

Figure 5 summarizes the differences with respect to the BRTS orbits for all four solutions. The RMS differences range from 1 to 9 m in height, 13 to 30 m in cross track, and 14 to 30 m in down-track, and the maximum difference over the entire ~3 day span is 52 m. (It should be remembered, however, that the down-track component of our orbit is constrained to match the BRTS orbit in the *bias* term via the range calibration.) This level of agreement is considered quite encouraging, and was somewhat unexpected given published estimates of the errors in the BRTS orbits. Especially encouraging are the results for TDRS-5, which was tracked at a very low elevation (10°). Moreover, the signature that TDRS-5 traced in the plane of sky was very compact compared to the one for TDRS-3. Despite these important differences, the TDRS-5 orbit accuracy appears only slightly degraded.

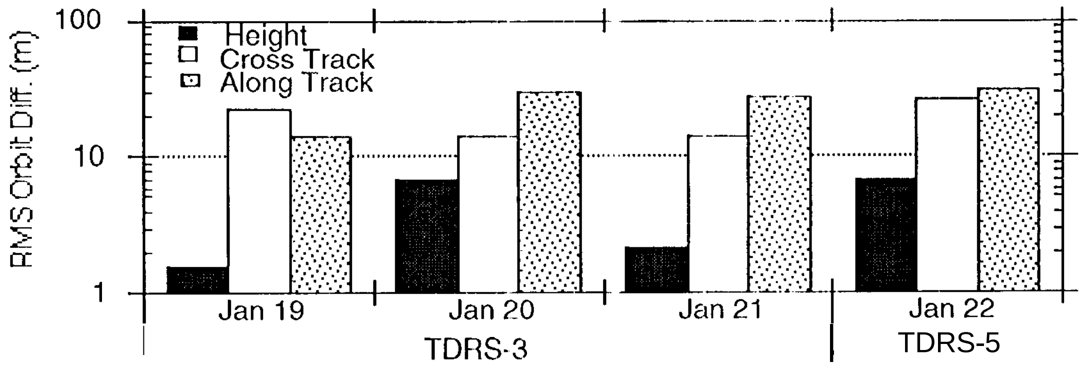

Figure 5. Bar graph summarizing RMS TDRS orbit differences (this study vs. BRTS). The first three solutions correspond to TDRS-3 and the last to TDRS-5. The arcs vary between 18 and 20 hours in length. The largest excursion over the entire set of comparisons is 52 m.

A critical requirement for TDRS orbit determination is the prompt recovery of the trajectory estimates after a station-keeping maneuver. In recognition of this, we have examined the effects of reducing the arc length on the error in the recovered orbit. Our nominal orbit solution for this comparison is a 34-hr arc for TDRS-3. Gradually shorter tracking data arcs were used in computing orbit solutions for comparison with this nominal ephemeris. Depicted in Figure 6 are the differences with respect to the nominal 34-hr solution; these results suggest that 75 m orbit precision is being approached with only 4 hours of tracking. The current requirement for STS is 200 m (1 σ) within 4 hours after a maneuver.[9] Differences of the 12-hr arc with respect to the nominal are less than 20 m in all components.

For improved accuracies in post-maneuver trajectory recovery, additional options can be explored. Since the short-baseline differenced phase data is not strong enough to recover the trajectory at the 25-50 m level from a cold start in a few hours, we would attempt to include the maneuvers(s) in the orbit solution arc. In the simplest approach, a velocity impulse could be estimated at the burn time. This approach has been applied successfully in the treatment of maneuvers of the GPS spacecraft.[17]

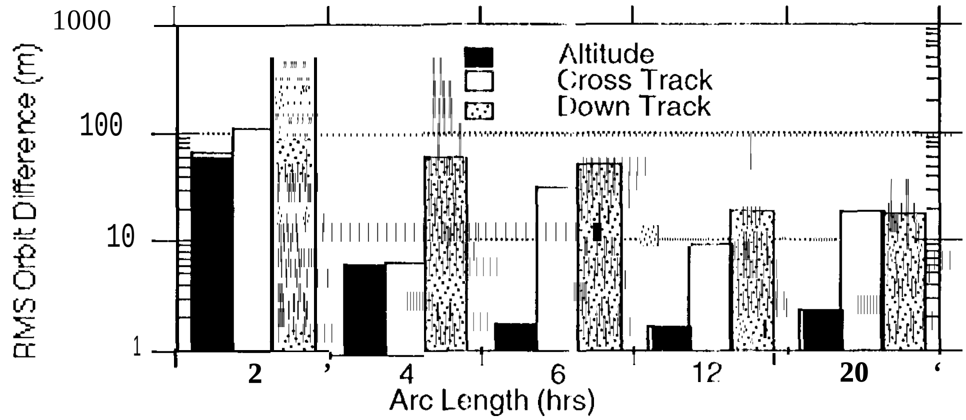

Figure 6. Effect Or solution arc length on precision of recovered '1'1)1{S-3 orbit. The orbit differences shown are taken with respect to a nominal 34-hr solution.

Future Demonstrations

We plan to perform a follow-up demonstrat ion of the GI.T concept for "1'1)RS mbit determination. This demonstration will attempt to address a number of outstanding issues concerning the operational viability of the system. To assist in the design of the demonstration, wc have performed a detailed covariance analysis. For this st udy, the towns of 1 .as Cruces, Truth or Consequences and Tularosa, New Mexico were selected for the tracking sites. These towns all lie within the main beams of the TDRS SGI .s and baselines among them form a triangle with -100 km legs surrounding the TDRS White Sands station. For the satellite, we used TDRS-5: its current position in the west slot renders it more interest ing from an operational standpoi at. The assumptions governing the covariance st udy were calibrated against the actual results from the January I 994 demonstration, and thus the estimation strategy given in '1'able 1 applies with a few notable exceptions. in contrast to the analysis of the actual data from January 1994, wc included certain "consider" parameters in the covariance analyses to yield more realistic error estimates. The consider parameters and their associated crrms (1σ) are given in Table 3. In keeping, with a conservative approach, the solar radiation pressure coefficient and WSC range bias were not estimated, rather they were treated as consider parameters. Also noteworthy is the absence of consider parameters for the location of the WSC range stat ion. In practice, the range station could be surveyed in with the remote TurboRogue stations at the cm level using a GPS survey. Any residual error would be negligible in comparison with the uncalibrated portion of the range bias.

Detailed results of the covariance analysis arc given in Ref. 113]. Wc limit the discussion herein to assessing the overal 1 TI)1-?S orbit accuracy and characterizi ng the impact of the WSC range bias. Figure 7 gives the expected 3-d orbit accuracy (RSS) for TDRS-5 as a function of the one-way uncertainty in the range bias. As di scussed earlier, the differenced phase data are relat ively insensitive to any bias in the longitude component of the satellite. A few range data points are needed to fully determine this component. Keeping in mi nd that that "consider" parameters scale in a linear fashion, it can be seen that the range bias emerges as the leading contributor to the orbit error once its one- way uncertai nt y exceeds -1 m. In order mai ntain the total root-sum-squared (RSS) orbit accuracy to 25 m or better, the range bias must be kept below 3 m (1 -way). This result applies in an approximate sense to TDRS satellites in the eastern slot as well, since the elevation as seen from WSC is nearly the same. If range data acquired from WSC cannot be calibrated to this level of accuracy in real time, then it is possible that range measurements could be obtained by tracking the SGL modulations (or tones) directly in the GPS receivers in addition to the phase of the carrier. This would require additional enhancements to the Turbo-Rogue packs.

TABLE 3. CONSIDER PARAMETERS FOR TDRS/GPS COVARIANCE ANALYSIS.

Consider Parameters	
TDRS solar radiation pressure coeff.	2 %
WSC range bias	1 m
WSC zenith wet troposphere (range)	10 Cnl
Ionosphere delay (K_u-band)	100 % Bent
Gravity model error	**50 %** JGM-3 - WGS-84
Tracking station baselines	1 cm East
	1cm North
	2 cm Vertical
X, Y Pole Motion	10 cm
UT1 - UTC	3 msec

Figure 7 also suggests that, with unbiased range measurements (< 1 m), the 3-d orbit accuracy (1 σ) for TDRS-5 can be brought below 10 m using the GLT technique. Though this remains to be demonstrated with actual data, it nonetheless underscores the remarkable precision of the differenced phase observables. That these measurements taken over very short baselines (- 100 km) have the potential to support 10 m orbit accuracy for a geosynchronous spacecraft is a testimony to the powerful ability of the GPS data to enable ultra-precise time transfer and reliable calibrations of atmospheric delays.

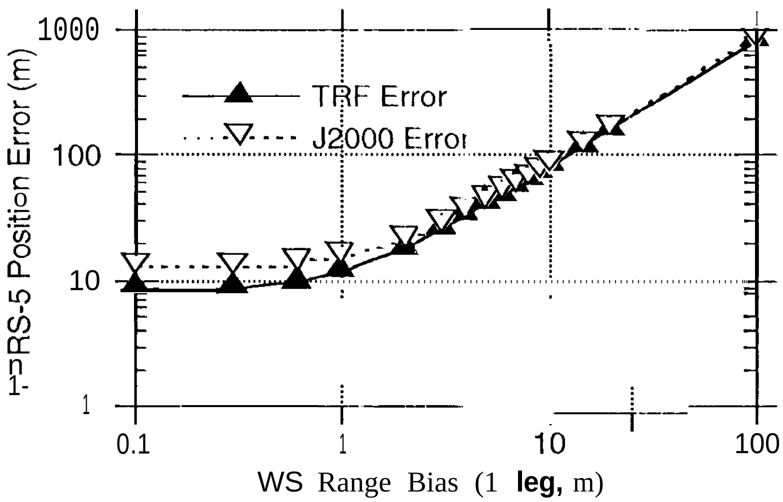

Figure 7. Expected Position Error for TDRS-5 (RSS) as a function of the one-way WSC range bias for 100 km network from covariance analysis. The orbit error is given in both the inertial (J2000) and terrestrial reference frames (TRF).

INMARSAT PRECISE ORBIT DETERMINATION

As a first step toward the eventual goal of a Global Navigation Satellite System (GNSS), INMARSAT is equipping their third generation geosynchronous spacecraft with specialized navigation payloads for augmenting GPS services.[18] These payloads will enable each of the four INMARSAT-3 spacecraft to broadcast a pseudo-GPS signal at the GPS L1 frequency (1575.42 MHz). This INMARSAT geosynchronous overlay (IGO) signal can be received in GPS receivers with only slight hardware and software modification and can be used for navigation and time transfer in much the same way that GPS signals are used. In addition, it will be used to disseminate GPS integrity information and wide-area differential con ections for use in mitigating the effects of Selective Availability y (intentional 1)OI) dithering of GPS clocks) and other common mode errors that impact real-t imc applications (e.g., aircraft navigation).

The keys to the efficacy of the IGO are the sa1 ne as those for GPS: accurate real-titnc knowl edge of the spacecraft positions, ant] precise calibration of the signal liming to a standard time reference (e.g., UTC). in contrast to the GPS spacecraft, the INMARSAT-3 spacecraft will not carry a suite of on-board atomic clocks to support accuiate positioning and time transfer. Instead, the IGO signal will be generated at specifically established satellite Earth stations, and will be steered to appear synchronous with the GPS satellite signals. Since only a single geosynchronous satellite signal is required to support fixed installations, the four INMARSAT-3 satellites will provide redundant worldwide coverage for precise time dissemination. Of course, the accuracy with which the timing can be controlled will depend on how well the position of the satellite is known. To fully exploit the timing and navigat ion benefits of the IGO, it wi I I therefore be necessary to know the orbital positions to an accuracy consistent with the GPS ephemeris error. The eventual goal is to determine the INMARSAT orbit ephemerides to the meter level or better.

in order to test the IGO concept, NAVSYS Corp. undertook an experiment using onc of the existing second-generation INMARSAT spacecraft. [19,20] The AOR- West spacecraft, presently stationed over the South America, carries a transponder capable of broadcasting a pseudo-GPS signal. For the experiment, a ground-station test bed designed and built by NAVSYS Corp. was deployed at tbc COMSAT Earth STAtion (ESTA) in Connecticut and used to generate a pseudo-GPS signal. The signal was relayed through the AOR-West transponder and tracked from two sites in the continental U.S. (Southbury, Connecticut and Boulder, Colorado). We used the GPS-like tracking observations to determine precise INMARSAT orbits. In contrast to the TDRS/GPS experiment, the IGO signals were not tracked in GPS receivers. On the other band, the baseline (South bury to Boulder) projected on tbc plane of the sky was much longer and the observations were derived from pseudo-CjPS transmissions rathei than simple phase measurements. The experiment thus brings to light complementary aspects of the GLT concept.

Experiment

The NAVSYS Corp. test-bed ground station (SIGGEN) at ESTA consists of the following components: 1) precision time and frequency reference; 2) controller; and 3) monitor/recei ver. The primary frequency standard is an HP 5071A clock with a cesium beam tube design that yields stabilities of $\pm 2 \times 10^{-12}$ s/s. The controller generates the IGO signal and steers its timing elements (a pseudo-random range code with the characteristics of the GPS Coarse/Acquisition or C/A code) so that they appear to be synchronous with the precise time reference of the ground station. In order to dynamically compensate for the group delays and frequency offsets, the SI GGEN monitor compares the return signal to the uplink. It also serves as a receiver for measuring the t we-way range from the IGO C/A code. A second monitor station was deployed in Boulder, where it was tied directly to a cesium clock at N] S'I'. Additional details on the design of the SIGGEN and the monitor stations arc given in Refs. [1 9-20].

Data for this experi ment were collected over a three day period in October of 1994. Prior to the experiment, NAVSYS engineers synchronized the HP time reference. at Southbury to NIST-UTC t i mc. The synchronization process is an iterative. procedure, and is ult in ately limited by knowledge of the range to the satellite and hence the accuracy of the available INMARSAT ephemerides.[19] For this experiment, we used AOR-West orbital elements from the INMARSAT operations center in London. Depending of the age of the orbital elements, errors in the modeled range to the satellite can reach a few kilometers, implying clock offsets of 10 μsec or larger.

Solution Strategy

Table 4 outlines the solution strategy for the INMARSAT precise orbit determination. The strategy is somewhat different than the GPS/TDRS solution strategy (cf. Table 1) owing primarily to the absence of GPS measurements. Since the IGO is single frequency L-band, the ionosphere delay can amount to several meters and emerges as an important source of error. Lacking dual-frequency GPS measurements to provide line of sight calibrations, we used the *Bent*[21] model to compute the delays. A nominal zenith troposphere delay was applied at both receivers; the zenith wet delay was fixed at 10 cm and the dry component (~2 m) was determined from the standard atmospheric pressure based on the elevations of the two tracking sites.

TABLE 4. ESTIMATION STRATEGY FOR INMARSAT ANALYSIS

Data Type	Data Weight
INMARSAT 1-way range (1/min)	5 m

Models and Constants	
INMARSAT Solar Rad. Pressure	Bus
INMARSAT Area/Mass Ratio	0.035 m^2/kg
Earth Gravity Field	Joint Gravity Model (JGM)-3
Luni/Solar Perturbations	JPL DE-200 Ephemerides
Ionosphere Range Delay	*Bent*[21] MODEL
Dry Troposphere Range Delay	Zen. computed from station height
Wet Troposphere Range Delay	10 cm zenith delay
Earth orientation/rotation	Intl. Earth Rot. Service (Bull. B)
Station Locations	WGS-84

Estimated Parameters	Parameterization	constraint
INMARSAT Epoch State	3-D epoch position	100 km
	3-D epoch velocity	10 m/s
INMARSAT Clock	Linear	1 s
		1 s/s
INMARSAT Solar Radiation Pressure Coefficient	Bias	100 %

Our treatment of errors in the clocks of the three participants (INMARSAT, ESTA, NIST) merits additional discussion. Although the master frequency generator for the SIGGEN is at the ground station in ESTA, it is instructive from the orbit determination standpoint to assume that the spacecraft carries the clock. A signal under active control is uplinked to INMARSAT at C band and then transponded and received at L band at each of the two receivers. Common view of the INMARSAT spacecraft from both ground stations provides for a means of estimating the INMARSAT clock error. Errors in the control loop of the uplink signal would be common to all receivers at the same time and would be indistinguishable from delays due to other common-mode errors, coming from e.g. the transponder. However, since the 1/min range data from the two ground sites were not collected with common time stamps, it was not possible to estimate the INMARSAT clock error at each measurement epoch, i.e. single differences could not be formed.

Instead, the INMARSAT clock error was estimated using a linear model over the length or the arc. We note that neither of the monitor stations in the October experiment were equipped with GPS receivers for dock synchronization. The clocks at the monitor stations were driven by stable cesium oscillators; nonetheless, there may be residual clock errors capable of mapping into the orbit in a systematic manner. in practice, the stations would be equipped with GPS receivers, eliminating these sources of error.

Orbit Determination Results

Three separate 34-hr arcs, overlapping by 17 hours, were processed using the strategy described above. Table 5 gives the statistics of the tracking data residuals and the formal (noise-only) orbit errors for these solutions. Postfit residuals of the C/A range data arc consistent at the level if 2-m (RMS). Examination of the residuals reveals only a hint of systematic behavior, with some mild periodicities at 12 and 24 hours.[20] Candidate explanations for these periodicities include residual errors in the SIGGEN control loop, residual clock errors, and mismodeling of atmospheric delay errors (e.g., ionosphere, troposphere.)

The statistics of the formal orbit errors were derived by mapping the initial condition errors over the duration of the solution arc. The smallest formal errors (cf. Table 5) arc in the radial component of the orbit. Larger errors in the cross- and ground-track components (5–15 m, RMS) could be reduced with a more favorable tracking geometry.

TABLE 5. RMS TRACKING DATA RESIDUALS AND MAPPED INMARSAT FORMAL ORBIT ERRORS.

S/C	Arc Epoch (UTC)	Range Obs.	RMS Range (m)	RMS Formal Errors (m)		
				Height	Cross Track	Down Track
INMARSAT	15-OCT 00:00	4080	2.50	1.74	14.7	5.09
	15-OCT 17:00	4080	2.52	1.69	14.2	5.10
	16-OCT 10:00	4080	2.56	1.76	14.7	5.22

Finally, we show in Figure 8 the statistics of the overlap periods. Note that while the first and third overlap periods are 17 hours, the central overlap is a single point (i.e., The first and last solution arcs share no common data). The RMS differences arc typically better than 10 m, suggesting that the precision of the orbits are at the same level. As there are systematic errors (c. g., clock biases, station coordinate errors) that can degrade the recovered orbit without manifesting themselves in the orbit consistency tests, these statistics should be interpreted with caution.

Covariance Analysis.

In order to improved INMARSAT orbit accuracies, a number of improvements to the current configuration should be implemented. Among them is the addition of one or two stations to improve the tracking geometry, and the use of carrier phase from INMARSAT in addition to C/A range. Also critical is the use of GPS receivers at the monitor stations. Clock errors, as well as atmospheric delays from the ionosphere and troposphere, can be calibrated by receiving the IGO signal in a dual-frequency GPS receiver that is simultaneously tracking the GPS constellation. With the exception of the ionosphere calibration, these capabilities have been amp] y demonstrated in the results of the TDRS/GPS experiment. The ionosphere calibration not critical for TDRS owing, to the high frequency (1 3.731 GHz) of the SGL transmission-- will be critical for the L-band IGO signal (1.57542 GHz). Dual-frequency GPS signals from the constellat ion are routinely used at J]']. to calibrate ionosphere delays for tracking of deep space probes. 'The software for performing this function could be adapted to compute the delay along the line of site to 1 NM ARSAT from each of the IGO ground stations.

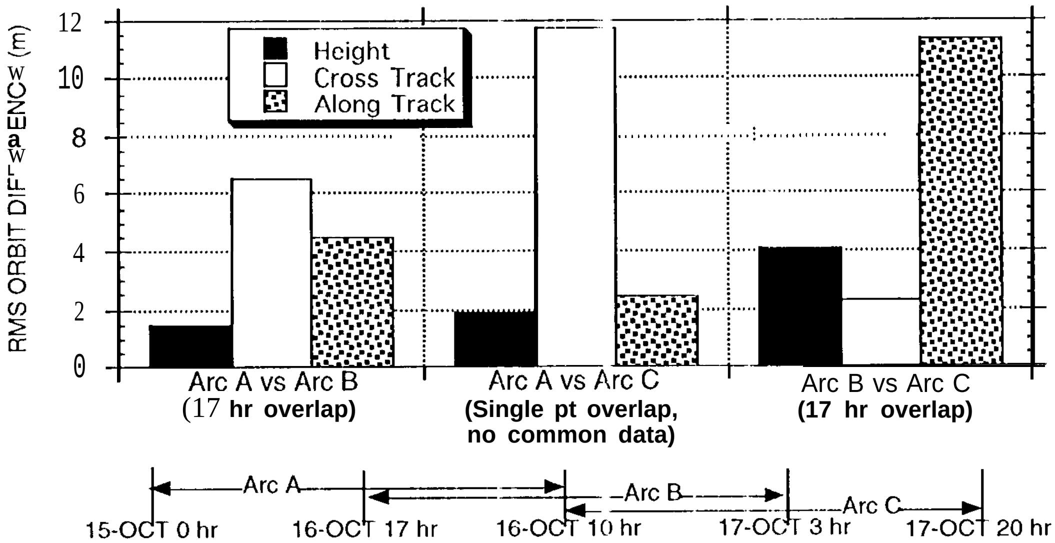

Figure 8. RMS Orbit Differences for overlapping INMARSAT Precise orbit solutions.

To answer whether 1-m orbit accuracies can be approached with the proposed system, we conducted a covariance st udy. Two ground stat ions—one at Leeds, UK and a second in Santiago, Chile- were added to improve the observabilit y. other assumptions are given in Table 6. Note that 1 NM ARSAT carrier phase measurement were included in the analysis, in addition to the C/A code range. Two parameters were treated as "consider" parameters: the solar radiation pressure coefficient for INMARSAT and the a scale parameter to account for residual errors in the ionosphere calibration along the line of site to INMARSAT. Earth orientation and rotation parameters were not considered, since the errors have little impact on the orbit in the terrestrial reference frame.

Depicted in Figure 9 are the statistics of the mapped orbit errors for a 34-hr solution. Under the assumptions in Table 6, the total RSS 3-d position error for INMARSAT is about 4 m. Most of this error is in the down-track component of the orbit, More important for IGO time transfer applications is the radial component, which in this case has an 1{. S magnitude of 1.4 m. We note that the RSS error in the radial component (not shown) is 1.4 m, which is adequate to support time transfer at the few-as level. Recent results from an expel iment conducted for the European Complement to GPS (CE-GPS) seem to corrobor ate that this level of orbit accuracy is achievable.[22] Using an experimental system with stat ions in Toulouse, France; Hartebeesthoek, South Africa and Kourou, French Guiana, *Barbier et al.* 22 report orbit overlaps of less than 4 m in total position for 1 NM ARSAT AOR-East.

What can be done to further improve the orbi t accuracy? 1 n practice, the impact of mismodeling the solar radiation pressure. will be mitigated by estimated the scale coefficient. In addition, the 10% estimate for residual ionosphere delays is somewhat pessimistic for typical conditions (D. Yuan, private communication, 1 995), With careful treatment and control Of these systematic error sources, it is reasonable to conclude that orbit accuracy consistent with the formal errors (2 m, 3-1)) can be approached. We speculate that further improvement (to the 1 -m level) is contingent on the addition of ground stations, and to a lesser extent on the improvement of the range quality. Further analysis is required to corroborate this.

TABLE 6. ESTIMATION STRATEGY FOR INM AR SAT COVARI ANCE ANALYSIS

Data Type	Data Weight
INMARSAT pseudorange (C/A)	5 m
INMARSAT carrier phase	1 cm
GPS pseudorange	1 m
GPS carrier phase	I m

Consider Parameters	Uncertainty
INMARSAT Solar Rad. Press. Coeff.	2 %
INMARSAT Ionosphere	10 % Bent Model for 1, I delay

Estimated Parameters	Parameterizat ion	constraint
INMARSAT Epoch Slate	3-D position	100 km
	3-1) velocity	1 m/s
GPS Epoch State	3-D position	1()() km
	3-D velocity	I m/s
Troposphere	random-walk zenith delay	40 cm; 5 cm/hr$^{1/2}$
GPS, INMARSAT and rcvr. clocks	white noise	I s
INMARSAT Solar Radiation Pressure Coefficient	Bias	1 00 %

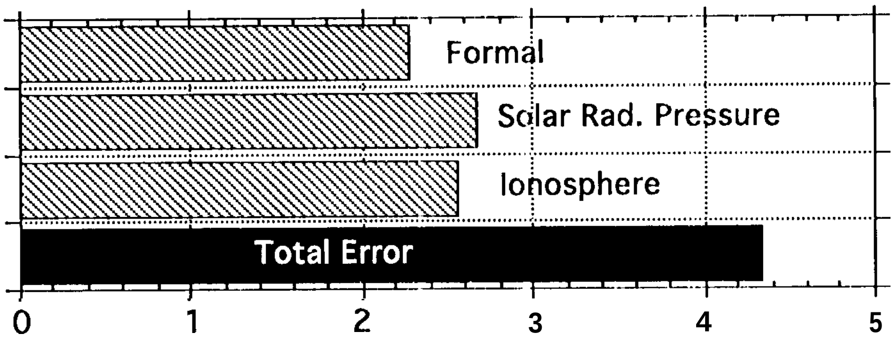

Figure 9. Relative contributions of various error sources for INMARSAT orbit determination based on covariance analysis. The exercise assumes a 4-station tracking network and 34 hour arc (cf. Table 6 for more details.)

D)1SCUSS1ON

The CilW-like tracking method offers several advantages for geosynchronous satellite tracking and orbit determination. Among them arc: 1) low-cost of the small antennae and enhanced GPS receivers in comparison 10 larger systems typically used for geosynchronous **tracking; 2)** accuracy rivaling connected element networks for the calibration of media, 1 {arth platform and timing errors from the simultaneous observation of GPS; 3) diversity of design configurations: from a small local area net work (e. g., TDRS) that emphasizes operational convenience and maintainability , to a global network that supports ultra-high precision (e.g. INMARSAT). 4) processing system that lends itself to a high-level of automation, even cm a desktop work stat ion. With respect to this last point, wc note that orbit determination procedures for the results given in this paper were run on HP work stat ions. The program sequences can be automated, as has been done for computing Topex/Poseidon orbits. In a recent demonstration of the Topex/Poseidon automated system, orbit estimates were delivered within 24 hours of the receipt of the flight data. For this exercise, a combination of orbit fits and predictions permitted achievement of 3-D accuracies better than 1 m (15 cm for the radial component) in real time.[23]

Similar benefits could be shared by other future missions adopting the GLT technique. In the case of the NASA Deep Space Network, which supports high-Earth orbiters in addition to deep space probes, valuable large antenna time could be freed up for more dedicated interplanetary tracking sessions. The high potential for inexpensive tracking should also be attractive to designers of NASA, military and commercial systems used for orbit determination of geosynchronous satellites.

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